Accelerator and Beam Physics: Grand Challenges and Research Opportunities

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Introduction

The Accelerator and Beam Physics (ABP) thrust is part of the DOE HEP-funded research portfolio, focused on General Accelerator R&D (GARD). Accelerator and beam physics is the science of the motion, generation, acceleration, manipulation, prediction, observation and use of charged particle beams. The ABP thrust focuses on fundamental long-term accelerator and beam physics research and development.

Vision statement

The ABP thrust explores and develops the science of accelerators and beams to make future accelerators better, cheaper, safer, and more reliable. Particle accelerators can be used to better understand our universe and to aid in solving societal challenges.

ABP missions

The primary scientific mission of the ABP thrust is to address and resolve the Accelerator and Beam Physics Grand Challenges, outlined below. Other equally important ABP missions are associated with the overall DOE HEP missions:

1. Advance the physics of accelerators and beams to enable future accelerators.
2. Develop conventional and advanced accelerator concepts and tools to disrupt existing costly technology paradigms in coordination with other GARD thrusts.
3. Guide and help to fully exploit science at the HEP GARD beam facilities and operational accelerators.
4. Educate and train future accelerator physicists.

Accelerator and Beam Physics Grand Challenges

Grand challenge #1 (beam intensity): How do we increase beam intensities by orders of magnitude?

Grand challenge #2 (beam quality): How do we increase beam phase-space density by orders of magnitude, towards the quantum degeneracy limit?

Grand challenge #3 (beam control): How do we measure and control the beam distribution down to the level of individual particles?

Grand Challenge #4 (beam prediction): How do we develop predictive “virtual particle accelerators”?

Proposed Accelerator and Beam Physics Research Areas

The research community input during the two ABP workshops [1, 2, 3] indicated the following areas of research are needed to address the above Grand Challenges:

- Single-particle dynamics and nonlinear phenomena; polarized-beams dynamics
  - This impacts GC 1 and 2 and benefits from addressing GC 3 and 4.
- Collective effects (space-charge, beam-beam, and self-interaction via radiative fields, coherent synchrotron radiation, e.g.) and mitigation
  - This impacts GC 1 and 2, and benefits from addressing GC 3 and 4.
- Beam instabilities, control, and mitigation; short- and long-range wakefields
  - This impacts GC 1 and 2, and benefits from addressing GC 3 and 4.
- High-brightness / low-emittance beam generation, and high peak-current, ultrashort bunches

    - This impacts GC 2, and benefits from addressing GC 3 and 4.
- Beam quality preservation and advanced beam manipulations; beam cooling and radiation effects in beam dynamics
    - This impacts GC 2, and benefits from addressing GC 3 and 4.
- Advanced accelerator instrumentation and controls
    - This impacts GC 3.
- High-performance computing algorithms, modeling and simulation tools
    - This impacts GC 4.
- Fundamental accelerator theory and applied math
    - This impacts all Grand Challenges.
- Machine learning and artificial intelligence
    - This impacts GC 3 and 4 in the short term and GC 1 and 2 in the long term.
- Early conceptual integration, optimization, and maturity evaluation of accelerator concepts
    - This focuses on science and technology gaps and bridges between various GARD thrusts.

Test facilities

Currently, there are several ABP research facilities, such as FACET (SLAC), AWA (ANL), ATF (BNL), BTF (ORNL), IOTA/FAST (FNAL) and facilities at universities. Such facilities are invaluable for advancing new accelerator concepts and technologies. It is critical to maintain and enhance support for these accelerator test facilities to keep them productive for ABP.

Education and training

It is critical to maintain support for the existing cross-cutting educational mechanisms in the field of accelerator science and technology (e.g. USPAS). Maintaining the workforce remains a challenge; and meeting it requires the availability of specialized courses and facilities suitable for hands-on training, as well as university-based research opportunities.

Integration of computational and ML tools across facilities

Effective coordination, maintenance and standardization of computational and ML tool development should be encouraged. Dedicated support of this would critically benefit accelerator and beam physics modeling across facilities.

References

[1] Workshop #1, **https://conferences.lbl.gov/event/279/**

[2] Workshop #2, **https://indico.fnal.gov/event/22709/**

[3] Summary document: **https://indico.fnal.gov/event/22709/page/2658-summary-folder**